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Risk of Sn burst in superconducting Nb₃Sn strands during reaction cycle.

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1 - Introduction.

During the heat treatment of the first Nb₃Sn High Field Dipole Prototype, Tin leakage has been observed in the inner bore of the coils. This report is an attempt to understand the reasons that may have leaded to this leakage.

2 - Compilation of the materials datas.

2.1 – Tin.

During the heating phase of the heat treatment Tin becomes liquid at around 232C. This phase change generates an increase of volume, which is supposed to lead to the wire burst. Using several bibliographic references, the density change and the equivalent thermal expansion in the solid and liquid phase has been calculated as a function of temperature from room temperature to around 750C.

Before melting at 232C Tin has several successive crystallographic structures, all of them having different specific volume, as shown in Table 1 (data from ref.1.). The density values of the beta phase vary from 7.29 g/cm³ (no temperature reference provided)(ref.1.) to 7.31 g/cm³ at 20C (ref.2.). A difference of the temperature of measurement can explain this scatter, so the value 7.31 g/cm³ at 20C has been used as reference. Each of the structural changes leads to a density change. These density changes seem not to have been observed during the thermal elongation reported in reference 3, from which the thermal expansion values have been used.

Name	Structure	Temperature domain	Density g/cm ³
Alpha	Tetrahedral cubic	Under 18C	5.81
Beta	Body centered tetragonal	18 – 161C	7.29
Gamma	Close packed hexagonal	161 – 232C	6.56

Table 1: successive structure of Tin.

The values used for the calculations correspond to the polycrystalline phase of Tin. The $\Delta l/l_0$ missing values have been calculated using the formula proposed in ref.2 which is:

$$\Delta l/l_0 = -0.525 + 1.354 \times 10^{-3} T + 1.587 \times 10^{-6} T^2 - 2.896 \times 10^{-10} T^3$$

for T expressed in Kelvin and $100 < T < 500$.

Several values of the density at melt and expressions for the density change as a function of temperature in the liquid state are proposed in ref.2. Using these data the density change and equivalent thermal expansion from room temperature to 650C has been calculated and is presented in Table 2 and Figure 1. Ref.4. proposes values for the specific volume as a function of temperature, unfortunately the density calculated using these values is not in accordance with the reference with the reference value at 20C. Ref.4. also proposes a value for the solidification shrinkage but this value is not in accordance the different density values.

T C	T K	Density g/cm ³	sol+liq dI/I %
20	293	7.3100	0.0000
127	400	7.2552	0.2510
227	500	7.1980	0.5160
232	505	7.1951	0.5296
233	506	6.9774	1.5644
250	523	6.9652	1.6236
275	548	6.9483	1.7061
300	573	6.9313	1.7888
325	598	6.9144	1.8718
350	623	6.8975	1.9550
375	648	6.8806	2.0385
400	673	6.8636	2.1224
425	698	6.8467	2.2064
450	723	6.8298	2.2908
475	748	6.8129	2.3755
500	773	6.7959	2.4604
525	798	6.7790	2.5456
550	823	6.7621	2.6312
575	848	6.7451	2.7170
600	873	6.7282	2.8031
625	898	6.7113	2.8895
650	923	6.6943	2.9762

Table 2: Density change and equivalent thermal expansion of Tin from room temperature to 650C.

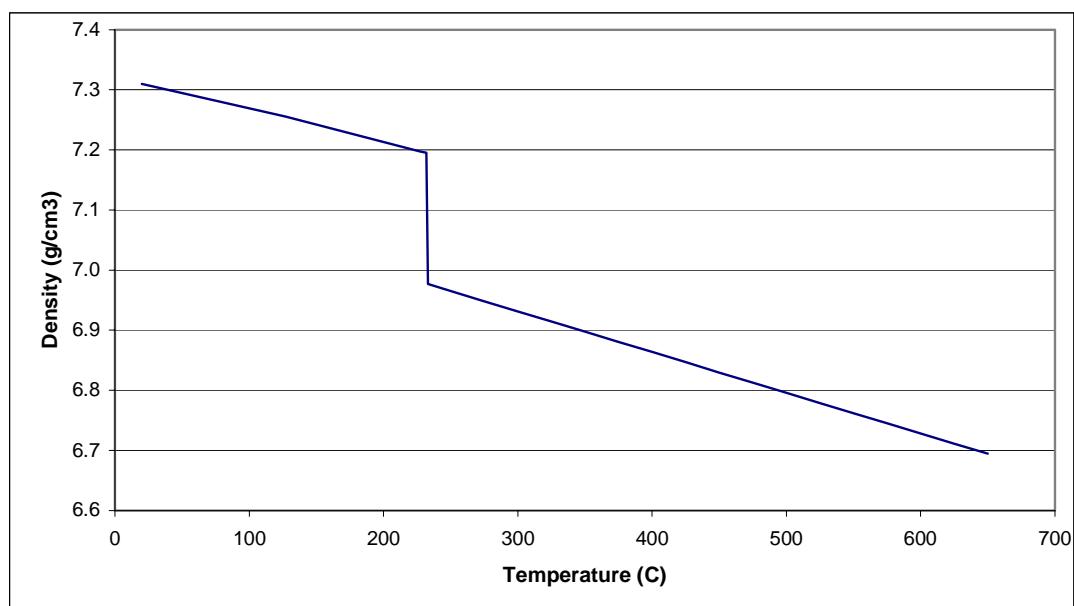


Figure 1: Tin density as a function of temperature.

2.2 – Niobium.

Niobium data have been found in ref.5. The thermal linear expansion values of Niobium come from ref.2 and are presented in table 3. The $\Delta l/l_0$ missing values have been calculated using the formula proposed in ref.2 which is:

$$\Delta l/l_0 = 7.265 \times 10^{-4} (T - 293) + 1.026 \times 10^{-7} (T - 293)^2 - 1.032 \times 10^{-11} (T - 293)^3$$

for T expressed in Kelvin and $293 < T < 2300$.

2.3 – Copper.

The thermal linear expansion values of Copper come from ref.2 and are presented in table 3. The $\Delta l/l_0$ missing values have been calculated using the formula proposed in ref.2 which is:

$$\Delta l/l_0 = 1.685 \times 10^{-3} (T - 293) + 2.702 \times 10^{-7} (T - 293)^2 - 1.149 \times 10^{-10} (T - 293)^3$$

for T expressed in Kelvin and $293 < T < 1300$.

2.4 - Niobium/Tin superconducting phase.

The thermal linear expansion values of Nb₃Sn come from ref.2 and are presented in table 3. The $\Delta l/l_0$ missing values have been calculated using the formula proposed in ref.2 which is:

$$\Delta l/l_0 = -0.187 + 5.49 \times 10^{-4} T + 3.296 \times 10^{-7} T^2 - 8.261 \times 10^{-11} T^3$$

for T expressed in Kelvin and $5 < T < 1300$.

2.5 – Niobium/Copper superconductor precursor.

The thermal linear expansion values of the Niobium/Copper precursor are estimated to be the average between Niobium and Copper values.

T C	T K	Copper dl/l %	Niobium dl/l %	Nb ₃ Sn dl/l %
20	293	0.000	0	0
127	400	0.182	0.078	0.08
227	500	0.361	0.155	0.16
327	600	0.549	0.232	0.243
427	700	0.741	0.312	0.33
527	800	0.939	0.393	0.42
627	900	1.147	0.477	0.513
727	1000	1.366	0.561	0.609

Table 3: Thermal expansion of Copper, Niobium, and Nb₃Sn from room temperature to 727C.

3 - Estimation of the strain induced in the outer copper shell during the heating phase of the reaction cycle.

3.1 - Wire properties

The wire properties are summarized in Table 4. A section of the wire is presented in Figure 2.

Parameter	OST Strand ⁽³⁾
Strand diameter, mm	1.001 ± 0.001
$J_c(12\text{ T}, 4.2\text{ K}), \text{ A/mm}^2$	> 1950
$I_c(12\text{ T}, 4.2\text{ K}), \text{ A}$	> 800
$d_{\text{eff}}, \mu\text{m}$	< 110
Cu, %	$> 48 \pm 0.3$
RRR	< 20
Twist pitch, mm/turn	13 ± 3

Table 4: wire properties.

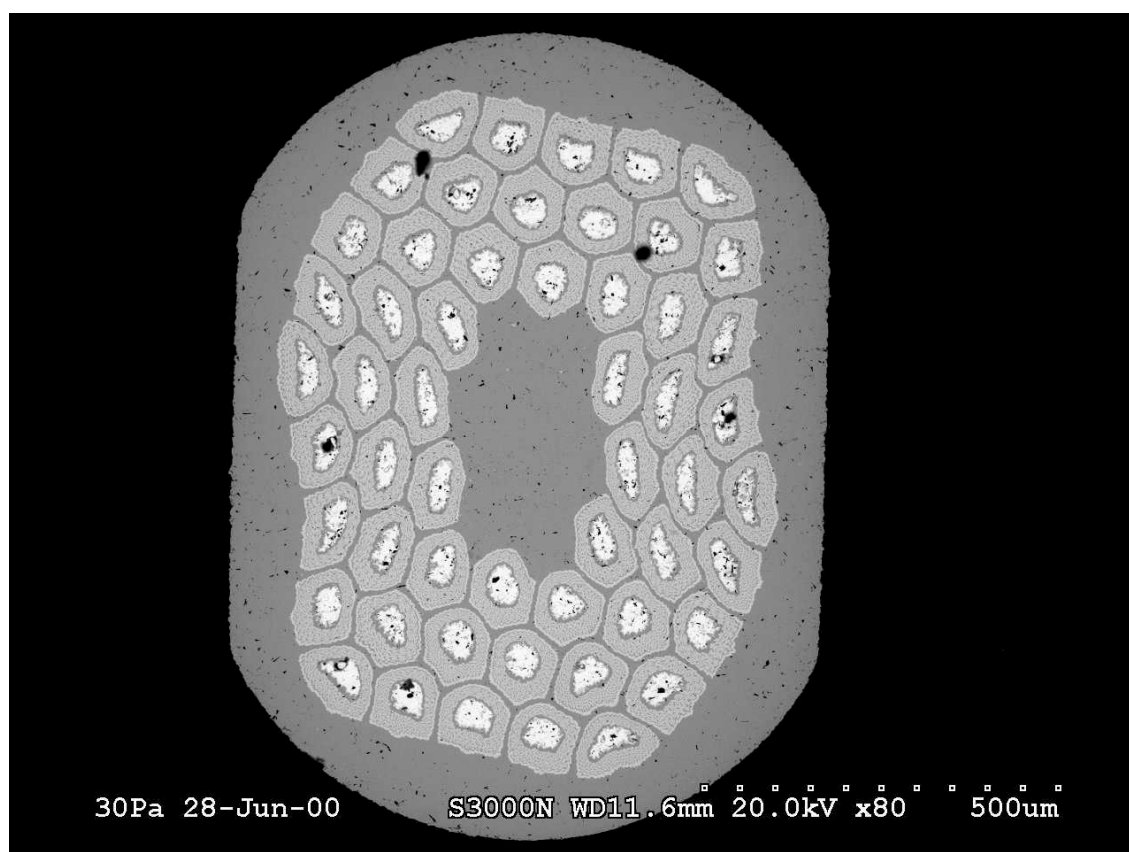


Figure 2: cross section of a cabled strand.

3.2 - Wire subelements modeling.

The cross section of the wire is modeled as 4 concentric tubes around a central copper core using the following assumptions:

- The central copper part is assimilated to a cylindrical core. The diameter of this cylinder is the mean value of different measurements of the copper core made from Figure 2. The external copper shell is assimilated to a tube, having the external diameter of the wire. Its internal diameter is calculated using the Cu/non Cu ratio to determine the total Copper section less the section of copper from the central copper core.
- The Tin section is calculated using the number of subelements and the average subelement Tin diameter. The subelements Tin cross section is estimated using subelement diameters measured on Figure 2. The Tin fraction is assimilated to a tube surrounded by two tubes of subelement non Tin material.
- The subelement non Tin material (Copper/Niobium, 50/50) is the wire section less the sum of non Copper and Tin section. The subelement non Tin material is assimilated to two tubes, one around the copper core and inside the Tin tube, the other around the Tin tube and inside the copper shell.

A scheme of this model is presented in figure 3.

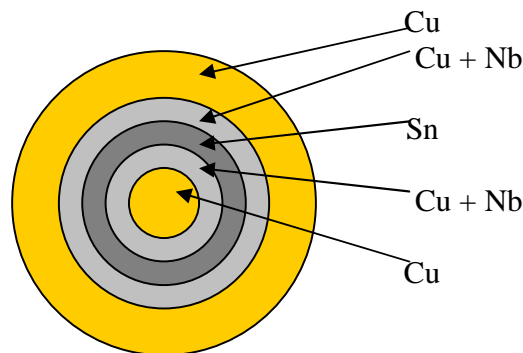


Figure 3: cross section of the strand model used to estimate the dimensional change.

3.3 - Dimensional change during the heat treatment.

From room temperature to 650C each of the materials will expand using the values presented in table 3, and several will suffer the expansion of their neighbors, especially when Tin will melt. Before melting the shear stresses appearing between the different materials due to their different thermal expansion behavior is neglected. All the diffusion effects between the different metals are also neglected. For all the materials the calculation is made in term of an increase of the material cross section. At the melt of Tin, assumption is made that no longitudinal expansion is possible, or that all the increase in volume generates an increase in the Tin cross section. Therefore the Tin section increase coefficient can be written:

$$(DS/S)_{\text{Tin}} = \frac{(1 + (dl/l)_{\text{Tin}})^3}{(1 + (dl/l)_{\text{Cu}})} - 1$$

During the increase of temperature, the central Copper core and the inner Copper/Niobium precursor will not suffer any dimensional change due to the melting of Tin. Only the outer Copper/Niobium precursor and outer Copper shell are affected, as shown in figure 4.

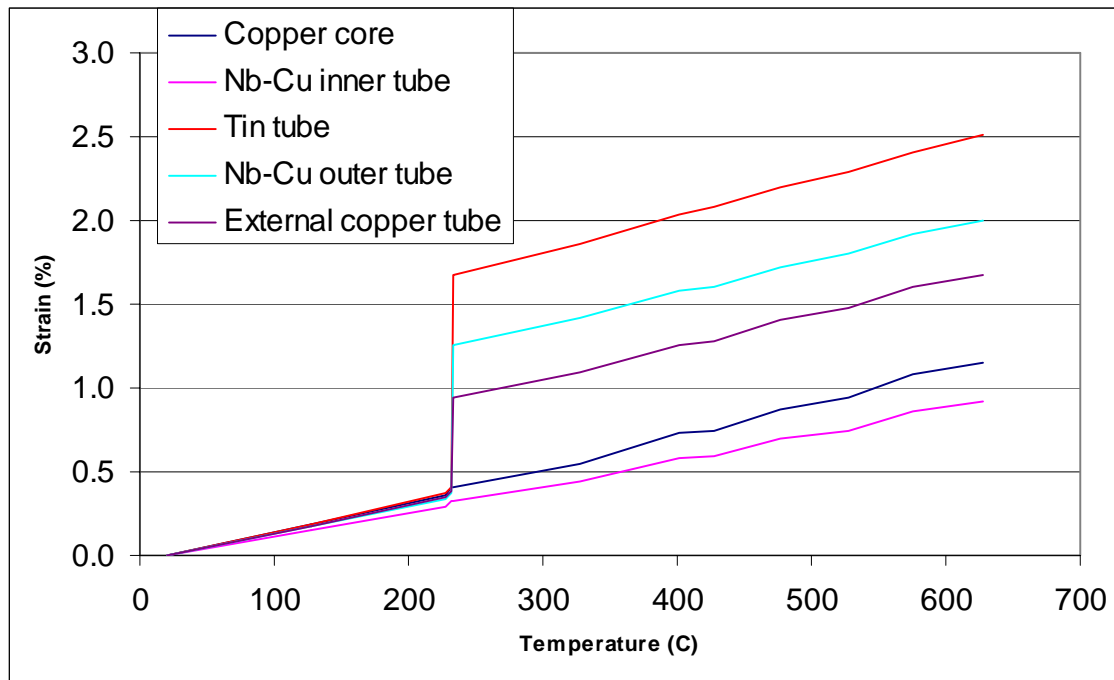


Figure 4: strain on the outer diameter of each component as a function of temperature.

From figure 4 it comes out that although the melting of Tin leads to an increase in diameter, the strain in the outer Copper shell (1.7 %) remains well below the fracture strain of Copper (between 14 % and 75 % from ref .6). The Tin melting effect alone can then not be considered as a credible explanation for the wire burst during the reaction cycle.

4 - Influence of the strain hardening of Copper.

During the drawing process of the strands the copper is plastically strained. This process generates defects and drastically reduces the strainability of copper. In order to recover its strainability the copper has to be heat treated. The annealing process consists of two steps, the recovery and the recrystallisation.

- The recovery consist of the displacement of dislocations, during this step two dislocations of opposite sign can be cancelled. At the end of the recovery the remaining dislocations are stacked in a sub-structure called wall of dislocations.
- The recrystallisation appears at higher temperature, when the walls of dislocations disappear to form new grain boundaries.

The temperature at which these effects appear is strongly dependant of the purity of the Copper, the foreign atoms acting often as stoppers for the displacement of dislocations, thus increasing the energy level required to move them. Annealing can start at temperatures as low as 200C while recrystallisation is effective around 400C.

The understanding of the burst requires looking more carefully at the metallurgical state at the end of the recovery state. When starting the heat treatment the wire is in the state corresponding to the end of the drawing, and the dislocations are randomly distributed in the copper. When the dislocations start to move and to stack to form the walls of dislocations the random distribution disappears Globally the quantity of defects reduces due the recombination of some of the dislocations, but locally in the wall of dislocations the density of dislocations increases. Locally the copper is then in a mechanical state corresponding to a greater strain. At that time if a new load is applied, the copper may break easily. The phase change of Tin becoming liquid is such a new load that it breaks the copper shell, the liquid Tin progressing though the wall of dislocation. It should be noted that this effect is enhanced if the ramp up of the temperature is greater than expected.

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